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Enhanced ac electrothermal fluidic pumping in microgrooved channels

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It is important to generate fast fluid flow yet maintain low temperature rise for ac electrothermal (ac ET) pumping in microsystems with conductive fluids. This has been generally the limitation of ac ET driven micropump applications. We present an enhanced ac ET pumping mechanism using low voltage ac signals that can result in a small amount of temperature rise. Different from the published traveling wave and asymmetric electrode structures positioned on insulated flat surfaces, channels with a microgrooved surface are utilized in this study. The effects of the microgroove existence on the modification of the ET body force and recession of the vortex backflows are demonstrated. Forward and backward pumping modes are identified and analyzed. This mechanism utilizes a thin film of asymmetric electrode structure on the microgrooved channel floor that can be fabricated with common planar lithography technologies. This study demonstrates that using the microgrooved structure can increase pumping capacity by five to sixfold as compared to a planar electrode arrangement with the same effective dimensions. © 2008 American Institute of Physics. [DOI: 10.1063/1.2977617]

I. INTRODUCTION

The ability to manipulate small amounts of fluid is of great importance for biomicroelectromechanical systems and laboratory-on-chip (bioMEMS and lab-on-chip) applications. ac electrophoretic effects such as ac electro-osmosis (ac EO), ac electrothermal (ac ET), and dielectrophoresis (DEP) have shown great promises in microfluidic pumping and particle separation/concentration applications.1–3

ac EO is a surface phenomenon where the interaction of the tangential component of the electric field at the surface and the induced charge in the double layer gives rise to a nonzero time-averaged surface force. The induced charge on the electrode surfaces is from capacitive charging4 and/or Faradaic charging.5 Due to the synchronous change in the direction of the tangential electric field as well as the sign of the induced charges, the direction of this surface force remains unchanged; thus, a steady-state fluid flow occurs. The working environment is limited to de-ionized water or low conductivity electrolytes (<100 mS/m). The applied frequency is below 100 kHz.1 On the other hand, ac ET is a volume force arising from the interaction of the electric field with the gradients in fluid permittivity and conductivity, generated as a result of thermal gradient. This thermal gradient is either from an external temperature gradient supply or generated as a result of thermal gradient. This thermal gradient is demonstrated to be able to enhance this electric traveling wave based micropumping system.5 One issue in this mechanism is that each electrode has to be independently and sequentially connected to the correct phase supply; thus, a complicated multilayer fabrication process is required. Another approach is by using a single-phase ac signal where an asymmetric electrode structure should be used to achieve a nonuniform electric field. This electric asymmetry as well as the thermal field breaks up the induced symmetric flow patterns8 over adjacent electrode pairs, as what happens in periodic electrodes with equal width. Therefore, biased vortices compete with each other and a resulting net fluid motion is established.

The reported planar electrode structures are, for instance, interdigitated electrode pairs with unequal widths6,12,13 and T shaped electrode arrays.5,6 Although fast fluidic flow was observed at the tip of the T shaped electrodes, the total pumping rate may be greatly weakened from the less efficient flow away from those tips. Electric asymmetry from electrochemical modification or surface change of the planar electrode structure was attempted in ac EO based micropumps.14 Nonplanar electrode structure has also been investigated. Urbanski et al.4 proposed an electrode structure for fast ac EO pumping, where each electrode contains a thick section and a thin section, thus turning into a stepped profile in the cross sectional view along the channel. Besides the electrode structures sitting on the channel floor, a sidewall vertical electrode structure was also utilized for particle manipulation based on the interaction of DEP and magnetohydrodynamic effects.15 This technique involves additional efforts in the fabrication process.

Theoretically, all electrode structures discussed can generate net pumping action if only they could break the symmetric competitive vortices over each electrode. In this case, the effective vortices perform as rollers propelling the fluid forward. However, the negative reversal fraction of these
rollers that contains speed as fast as the positive obverse fraction can greatly reduce the total pumping capacity. This paper addresses the feasibility of recessing those reversal flows by the microgrooves on the floor of an ac ET pumping channel. We investigated the effects of the folded and tilted electrodes due to the sloping groove surfaces upon ET driving forces. The pumping effectiveness of different groove profiles is discussed and analyzed to guide optimum ac ET pumping design.

II. AC ET FLUID FLOW

ac ET force arises from the interaction of the electric field $E$ and local variations in fluid conductivity $\sigma$ and permittivity $\varepsilon$. These gradients in fluid conductivity and permittivity are induced from a nonuniform thermal field generated, for instance, as a result of a high frequency oscillating electric field applied through a conductive fluid. The energy source from this ET effect, also known as Joule heating, is written as

$$k\nabla^2 T = -\alpha(E^2).$$

The time averaged ac ET force $\langle f_E \rangle$ is described as

$$\langle f_E \rangle = \frac{1}{2} \frac{\varepsilon(\alpha - \beta)}{1 + (\omega \tau)^2} (\nabla T \cdot E)E - \frac{1}{4} \varepsilon \alpha |E|^2 \nabla T,$$

with $\alpha = 1 / \varepsilon (\partial \varepsilon / \partial T) = -0.4\% \text{ K}^{-1}$, $\beta = 1 / \sigma (\partial \sigma / \partial T) = 2.0\% \text{ K}^{-1}$ (Ref. 16), and charge relaxation time $\tau = \varepsilon / \sigma$, where $\nabla$ depicts the gradient, $\omega$ is the electric angular frequency, and $T$ is the temperature.

The imposed electric volume force $\langle f_E \rangle$ on the fluid gives rise to a visible flow in the microfluidic environment. The equation for the time-averaged component of the steady-state fluid motion can be obtained from

$$0 = - \nabla p + \eta \nabla^2 u + \langle f_E \rangle + \Delta u \rho g,$$

where $p$ is the pressure, $g$ is the gravitational acceleration, and $\eta$ and $\rho$ are the viscosity and density of the fluid, respectively. The changes in density can be neglected due to the minimal buoyancy force in our cases. Therefore, the induced fluid velocity and temperature rise are found to be proportional to the fourth power of the electric field and square electric field as $u_{ACET} \propto V^4$ and $\Delta T \propto V^2$, respectively.

III. AC ET PUMP DESIGN

The previous governing equations indicate that net pumping action can be enhanced by fortifying ac ET body force, namely, the interaction of the electric field and thermal gradients. Obtaining a high pumping rate under acceptable temperature rise with low voltages would be a novel objective for a micropumping design effort.

In contrast to the electrodes sitting on the insulated flat surfaces and those modified electrode geometries in most ac electrokinetic based pumps, the presented electrode structure is deposited on the grooved surfaces as shown in Fig. 1. Within the structure of planar surfaces, vortices over the edge of each electrode drag the bulk fluid forward (left-hand direction as shown in the figure) with its top section while impedes the bulk fluid motion with its bottom section. In this case, grooved surface is initially presented to accommodate the bottom reversal section of the vortices in order to achieve a unidirectional fluid motion through the channel height. Due to the folded and tilted electrodes induced by the grooves, electric field strength and thermal gradient are expected to be fortified in the direction of the net flow. This would greatly benefit ac ET force generation. Good thermal conduction is also advantageous in the ac ET mechanism to achieve high thermal gradient while restricting total temperature rise. In our cases, a Si substrate instead of commonly used glass is utilized and preferable. Improvement of pumping capacity from the ac ET mechanism is thus expected.

In consideration of the fabrication feasibility, the grooves can take various forms such as round grooves, U grooves, V grooves, and rectangular grooves as shown in Fig. 2. The study will be focused on the case of U grooves and the case of a combination of U and V grooves (U&V). The theoretical analysis and numerical simulation will address the modified coupling effects of the electric field and thermal gradient and the recessed reversal flows by these grooves. The potentials of the presented structure in enhancing ac ET pumping action are discussed in the following sections.
The activity and permittivity of the fluid are boundaries are defined as insulated/symmetry. The conductors are applied to the electrodes while the rest of the that of the fluid cannot be simply fixed at ambient temperature. Si substrate cannot be simply fixed at ambient temperature. For Si, these parameters are specified as 130 W kg K, and 4.184 kJ kg K, and 1000 kg m3, respectively. In the fluidic domain, the fluid is included since the conductivity of the channel structure and insulation layer (SiO2 or Si3N4) is much lower than that of the fluid (0.01 to approximately a few S/m). Electric potentials are applied to the electrodes while the rest of the boundaries are defined as insulated/symmetry. The conductivity and permittivity of the fluid are 0.1 S/m and 80 e0, respectively. In the thermal domain, the top boundary is defined as adiabatic, and all the other boundaries are fixed at ambient temperature, including left-hand and right-hand boundaries that are far away from the heating source. For the fluid, thermal conductivity, specific heat, and density are 0.598 W m K, 4.184 kJ/kg K, and 1000 kg/m3, respectively. For Si, these parameters are specified as 130 W/m K, 0.7 kJ/kg K, and 2329 kg/m3, respectively. In the fluidic domain, all the surfaces are assumed to be no-slip boundaries except the left-hand and right-hand boundaries as zero pres-

IV. BOUNDARY CONDITIONS

The presented ac ET pumping system can be developed by common microfabrication technologies. Deposition of a thin electrode layer is after Si substrate etching and insulation. The microfluidic channel can be either fabricated through photolithography (for instance, SU-8 photoresist then covered by a slide glass) or through soft lithography (for instance, polydimethylsiloxane molding). It is indicated that the thermal properties of the substrate have great effects on pumping action in the ac ET mechanism and electrodes cannot be simply fixed at ambient temperature. Si substrate with thickness of 500 μm is thus included.

There are three modeling domains coupled in this ac ET problem as analyzed previously. The schematic diagram of modeling domains and the boundary conditions are shown in Fig. 3. The clear area is the solution space for thermal and electric problems. The dark and clear areas are the solution space for thermal problems. In the electric domain, only the fluid is included since the conductivity of the channel structure and insulation layer (SiO2 or Si3N4) is much lower than that of the fluid (0.01 to approximately a few S/m). Electric potentials are applied to the electrodes while the rest of the boundaries are defined as insulated/symmetry. The conductivity and permittivity of the fluid are 0.1 S/m and 80 e0, respectively. In the thermal domain, the top boundary is defined as adiabatic, and all the other boundaries are fixed at ambient temperature, including left-hand and right-hand boundaries that are far away from the heating source. For the fluid, thermal conductivity, specific heat, and density are 0.598 W/m K, 4.184 kJ/kg K, and 1000 kg/m3, respectively. For Si, these parameters are specified as 130 W/m K, 0.7 kJ/kg K, and 2329 kg/m3, respectively. In the fluidic domain, all the surfaces are assumed to be no-slip boundaries except the left-hand and right-hand boundaries as zero pres-

V. RESULTS AND DISCUSSION

We use a commercial finite element package COMSOL Multiphysics (Ref. 17) to solve the coupled equations. The structure dimensions are given in Fig. 1. All the calculations are based on the time-averaged parameters. Meshing density is intensified at the locations of the grooves. Figure 4 shows the electric field magnitude and induced fluid velocity as a function of meshing density at three selected points (1, 5, and 50 μm) above the concave corner of the large electrode as specified in Fig. 3. Stable convergence is experienced in the numerical iteration, and geometrical singularities (sharp corners) are avoided by the mesh refinement method. This trend has been observed in other locations with sharp corners.

A. Buoyancy and ac EO effects

Buoyancy and ac EO effects are present simultaneously with ac ET effects. Buoyancy force is obtained from

$$f_b = g \rho \beta T = g (\partial \rho / \partial T) \Delta T,$$

with $1/\rho (\partial \rho / \partial T) = -0.0002$ K-1. The ratio of the ac buoyancy force to ET force is thus approximated as $f_b/f_E = 2$.
\( \times 10^{-2} \rho g \Delta T/e(\nabla T \cdot E) = 1/e - 6 \) in the presented systems. 
In the ac EO mechanism, the driving force is the surface force from the interaction of the tangential component of the electric field and the induced surface charges. The slip velocity \( u_{\text{slip}} \approx V^2 \) is two orders smaller than ac ET flow \( u_{\text{ac ET}} \approx V^2 \) (Refs. 1 and 2) even disregarding that the ionic double layer will be suppressed in a high conductivity fluid and lack sufficient time to accumulate under such high electric frequencies.\(^1,4\) Therefore, ac EO effects and temperature gradient induced buoyancy force are neglected in the numerical simulations, which is similar to the situations depicted in Ref. 9.

**B. Pumping modes**

Two distinct situations for ac ET volume force can be identified as

\[
\langle f_E \rangle \approx \frac{(\alpha - \beta)e}{2}(\nabla T \cdot E) = -0.011 e E^2 \nabla T \text{ when } \omega e \ll 1,
\]

\[
\langle f_E \rangle \approx -\frac{\alpha}{4} e E^2 \nabla T = 0.001 e E^2 \nabla T \text{ when } \omega e \gg 1.
\]

(5)

Within different frequency ranges, ET body forces are dominated by either Coulomb or dielectric force components. These two components are in opposite directions and give rise to forward and backward flow motions. Therefore, the fluid is driven by the same force field governed by the common factor \( e E^2 \nabla T \) with different coefficients (\( -0.011 \) versus \( 0.001 \)) under different frequencies. In this case, the pumping capacities at these two modes can differ approximately by an order of ten.\(^1\) Around the critical frequency where \( \omega e/\sigma \approx 1 \), the ET body force becomes very weak due to the competition of these two forces resulting in a stationary mode with no net pumping actions. This is different from the traveling wave situation where maximum pumping capacity occurs at this critical frequency.\(^9,10\)

**C. Pumping capacity enhancement**

The enhancement in the pumping capacity of the grooved surface structure exhibits two aspects. First, it is straightforward that grooves are capable of holding the reversal flow fraction of the vortex rollers. Estimation of the vortex size in terms of both height and width is important for the groove design to achieve high performance. Shallow grooves are not able to sufficiently consume the backward part of the rollers, while deep grooves may overconsume the effective propelling part of the rollers and bring difficulty in the fabrication process.

Second, the more important benefit from the grooved surface rests with the redistribution of the electric field and thermal gradients. Due to the sloping surfaces of the grooves, the deposited electrode structures are either folded (large electrodes) or tilted (small electrodes). As a result, electric and thermal fields are changed as shown in Fig. 5. In both U and U&v grooved surface structures, thermal gradients \( \nabla T \) at the sloping surfaces are strengthened by the temperature difference between the substrate and the fluid medium within the channel. The magnitude of the electric field at those sloping surfaces is also fortified in the direction along the channel. Near the vertex of each ridge, the component \( \langle \nabla T \cdot E \rangle \) of \( \langle f_E \rangle \) is greatly fortified in the pumping direction except the one at the backsloping surface of the small grooves. This strengthened ET force will propel forward the fluid over the top side of the grooves. Combined with the previous backflow recession within the sufficiently deep grooves, the streamlines of the fluid flows will therefore be highly stretched. The only minor reversal flow induced by the negative ET force at the backsloping surface opposite to the small electrode will be restricted by the boundaries and overwhelmed by the strong forward fluid motion in U&v grooved structures. As a result, the fluid will be uniformly driven forward in a smooth gliding mode, and the pumping action will be fortified mostly in the U&v grooved structures.

The calculated fluid velocities confirmed and quantified these observations. Result shows that major U grooves under large electrodes can improve pumping capacity by two to three times, and minor v grooves under small electrodes can improve by an additional two to three times due to the strengthened component of \( \langle \nabla T \cdot E \rangle \) in the vicinities of each electrode pair. Figure 6 shows the simulated results for both flat surface structures and grooved surface structures. The fraction of reversal flow of the vortex rollers impairs the net pumping action as shown in Figs. 6(a) and 6(b). Especially in the case of flat surface structure, the reversal flow fraction of rollers above both large and small electrodes is as
fast as the forward flow components. In contrast, no reversal flow appears in the U&v grooved surface structures as shown in Fig. 6. Figure 7 shows the velocity field at three levels over each nongrooved/grooved surface as 1, 5, and 20 \( \mu m \), respectively. In the vicinities above the electrodes, strong electric field and thermal gradient \( \nabla T \) induced strong ET body force drives the fluid at maximum speed in an order of 1–2 mm/s as shown in Figs. 7(a) and 7(b). Away from these vicinities, fluid speed decreases due to electric/thermal field weakening as well as the no-slip boundaries from the top surface as indicated in Fig. 7(c). At each distance level above the bottom surface, the fluid speed is much higher in the U&v grooved structure than in the other two structures. All these factors contribute to a uniform fluid motion in the grooved surface structure especially when U&v grooves are utilized in the floor of the microfluidic channel.

D. Temperature rise

Heat generation is an important concern in an ac ET mechanism especially for high conductivity fluid manipulation. Excessive heat should be restricted for biochemical applications where temperature sensitive chemicals or bioparticles are involved. The variation in temperature \( \Delta T \) is approximately equivalent to \( \sigma V^2_{rms}/k^2 \). The maximum temperature rise is determined by the electric field strength. Therefore, large \( \nabla T/\Delta T \) is decisive for ac ET based pumping systems. The temperature rises are almost consistent due to the fixed ratios of the effective dimensions of the interdigitated asymmetric electrodes structure. Therefore, modification of the electrode geometry from the introduction of surface grooves changes the electric and relevant temperature distributions but does not affect the maximum temperature rise. As depicted in Fig. 6, the maximum temperature rise occurs at the adjacencies of each electrode pair. The maximum temperature rise is around 2 K under the operation conditions as listed in Fig. 1. This correlates with the results presented in Ref. 2 where the measured temperature for a solution with conductivity of 0.01 S/m is around 1 °C at 20V\(_{p-p}\) in a pair of electrodes with 20 \( \mu m \) interspace.

The ac ET driving force is proportional to \( eE^2\nabla T \) as indicated in Eq. (4). At microscale, local thermal gradient \( \nabla T \) induced by Joule heating is much higher than that caused by the external temperature difference under the same working conditions. The introduction of external heat sources could complicate the system and make it difficult to control the thermal gradient precisely within the microfluidic environment. This indicates an advantage of internal Joule heating techniques over the applications of external temperature gradient as in the ac ET micropumping system.
VI. CONCLUSION

Enhanced ac ET micropumping in the microgrooved surface channels at low voltage ac signals has been examined. Microgrooves presented great capacity in backflow recession as well as ET force magnification. The microgrooved surface channels are capable of producing uniform fluid motion at faster speeds. The simulation results indicate that U grooves under large electrodes can improve pumping capacity by two to three times compared to the flat surface arrangement, and v grooves under small electrodes can improve pumping capacity by an additional two to three times. Many other groove profiles are also applicable besides the U and U&v grooves utilized in this study. The pumping rate could be easily scaled up by increasing the width of the channel or reducing the dimensions of the electrode structure. This design provides a promising mechanism for high conductivity fluid manipulation, yet with limited temperature rise. It is expected that the presented asymmetric electrode structure based on grooved surface channels can also be utilized to enhance other electrokinetic pumping system such as ac EO based microfluidic pumps.